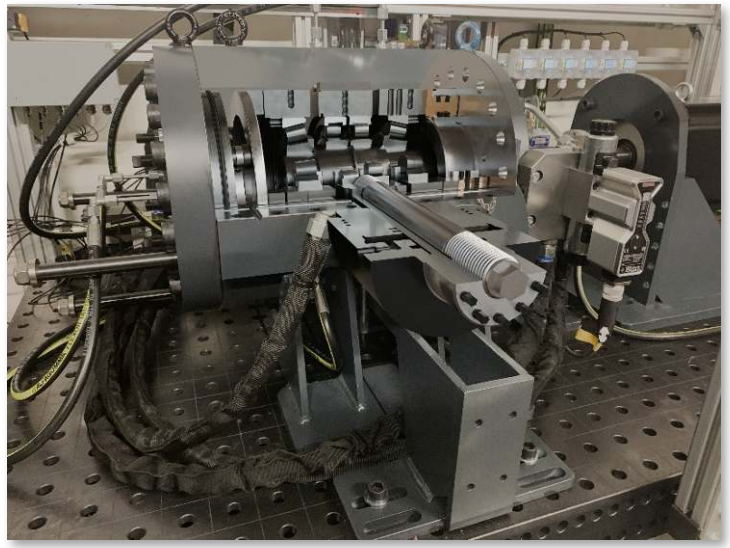
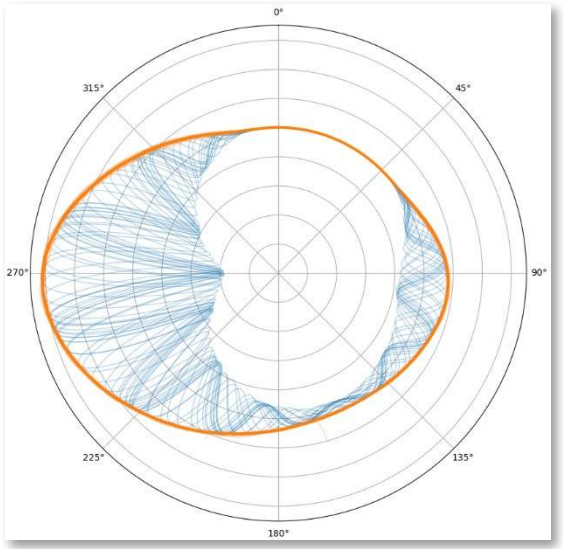
# Analysis of kinematics and load distribution of rolling elements in a wind turbine gearbox bearing under dynamic conditions

Martin-Christopher Noll, i4M technologies GmbH
Prof. Dr. Matthias Stammler, Fraunhofer IWES
Dr. Valentin Meimann, MML Service Solutions GmbH

Wind Bearing Forum 2025, 24.09.2025, Hamburg










Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Outline

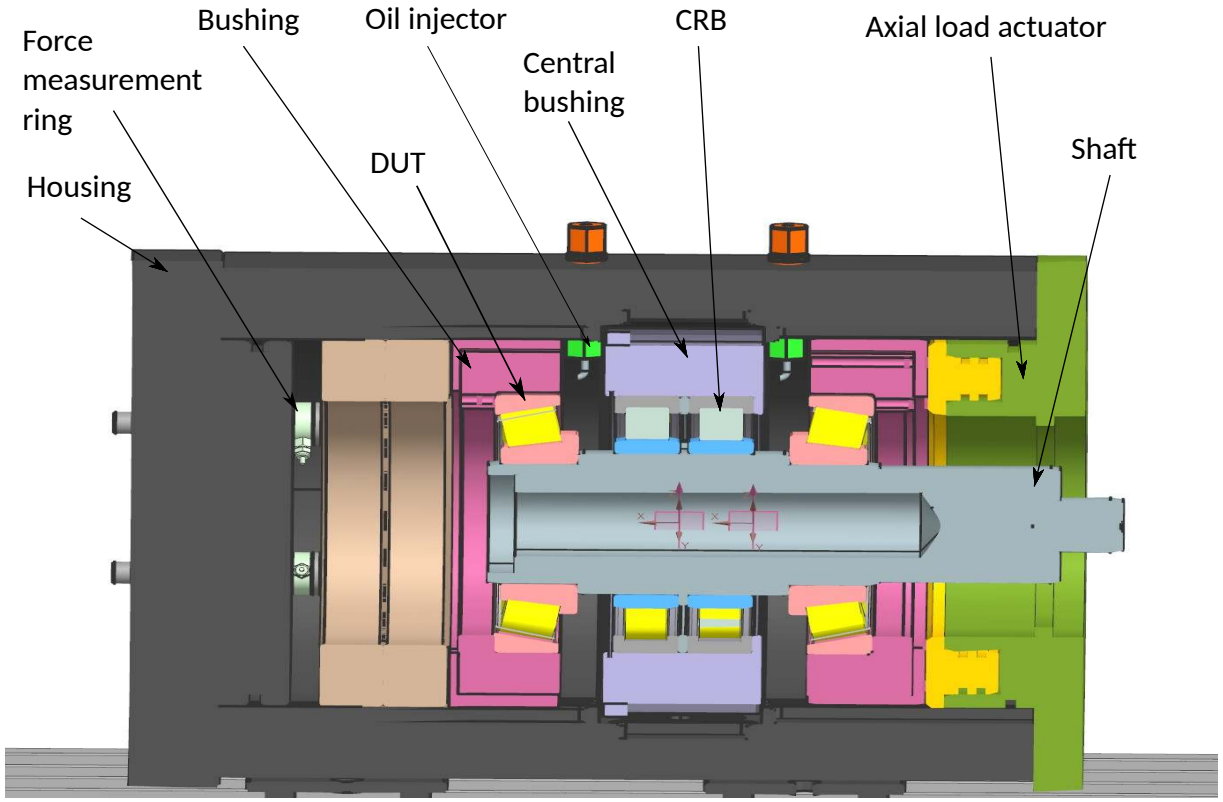
1. Introduction, overview, and motivation
2. Test bench setup and bearings
3. Rolling element-integrated measurement technology
4. Data and analysis methods
5. Results
6. Summary and outlook

# Outline

1. Introduction, overview, and motivation
2. Test bench setup and bearings
3. Rolling element-integrated measurement technology
4. Data and analysis methods
5. Results
6. Summary and outlook

# Introduction: Dy-rex Project

- **„Dy**namische **Re**gelung einer a**x**ialen Lastsuperposition“ (Dynamic control of axial load superposition)
- Reduction of harmful rolling element slip while maintaining fatigue life
- Application in critical operating situations such as fault ride through
- Motivation: Reduction of WEC






Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Introduction: Dy-rex Project

- **„Dy**namische **Re**gelung einer a**x**ialen Lastsuperposition“ (Dynamic control of axial load superposition)
- Reduction of harmful rolling element slip while maintaining fatigue life
- Application in critical operating situations such as fault ride through
- Motivation: Reduction of WEC





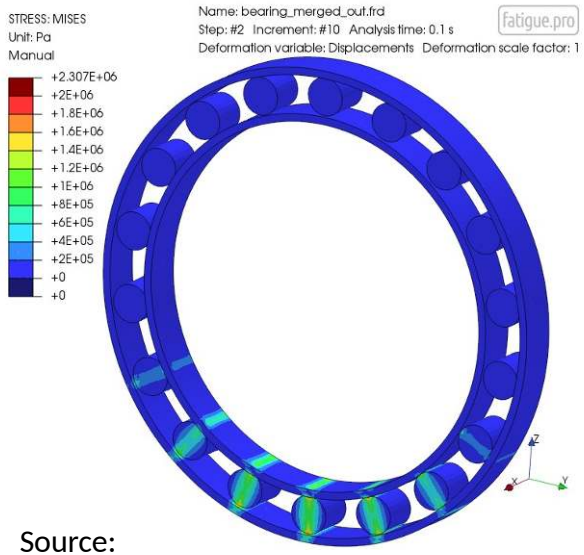
Fraunhofer IWES
i4M technologies GmbH intelligence for mechanical systems

# Questions and motivation behind this presentation

- How is the load distributed among the various rolling elements in the orbit of a rolling bearing?
- At which points and in which operating ranges does harmful slip occur?
- High relevance for design and reliability calculations
- Reliability is a dominant issue, especially in the field of wind energy
- Simulations only reflect reality to a limited extent; measurements are always necessary for validation
- Measurements of load distribution and slip in rolling bearings are technically challenging



Source: Schaeffler




Source: fatigue.pro



Fraunhofer IWES

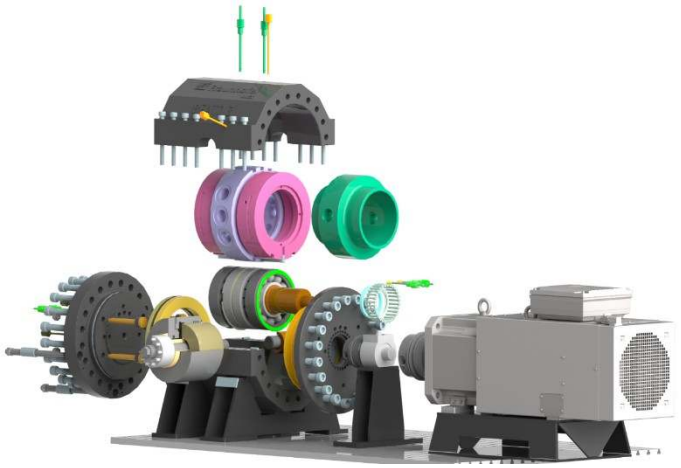
i4M technologies GmbH intelligence for mechanical systems

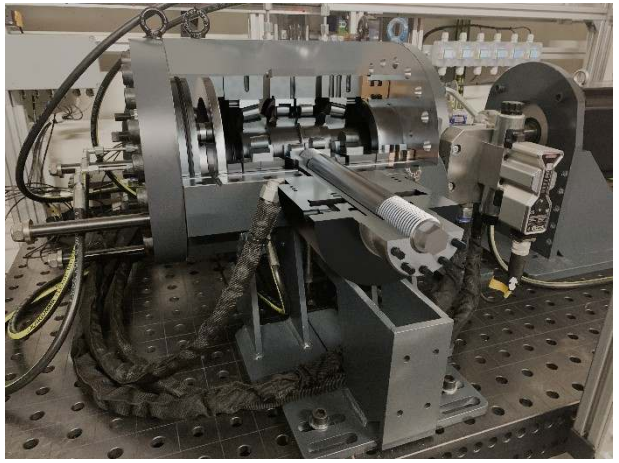
# Outline


1 Introduction, overview, and motivation
2 Test bench setup and bearings
3 Rolling element-integrated measurement technology
4 Data and analysis methods
5 Results
6 Summary and outlook

# Test bench setup & storage

- Test bench BEAT0. 3
- Designed for high load and speed dynamics
- Possible roller bearings: 30318, 7318, as well as four-point types
- Ten adjustable oil feeds
- Bearing bushes as hydrostatic plain bearings
- Radial force applied by two tension cylinders controlled by a valve
- **Load is applied on horizontal axis**





| Parameter | Value | Unit |
|---|---|---|
| Max. RPM | 3000 | rpm |
| RPM-Dynamic | 500 | rpm/s |
| Max. Axial Force | 140 | kN |
| Axial Force Dynamic | 1120 | kN/s |
| Max. Radial Force | 250 | kN |
| Radial Force Dynamic | 500 | kN/s |
| Max. outer diameter of test bearing | 220 | mm |
| Max. flow rate for oil lubrication | 60 | l/min |



Fraunhofer IWES
i4M technologies GmbH intelligence for mechanical systems

# Outline


1 Introduction, overview, and motivation
2 Test bench setup and bearings
3 Rolling element-integrated measurement technology
4 Data and analysis methods
5 Results
6 Summary and outlook

# Rolling element integrated measurement technology / i4M Smart Roller

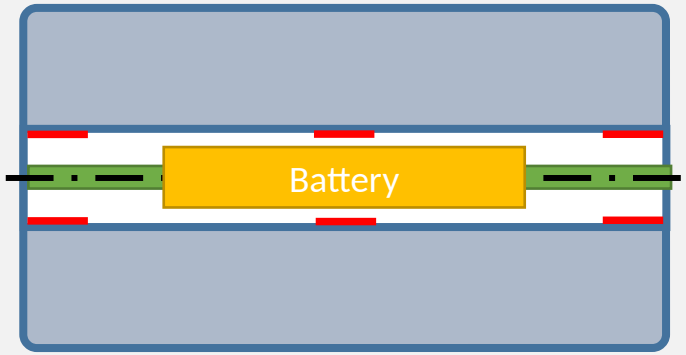
- Different Smart Roller Options

Electronics — Strain Gage — Battery

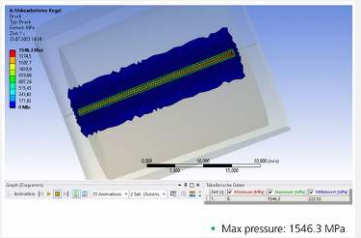
- Smaller Rollers (< 40 mm in diameter)
  - Rechargeable / non-rechargeable
  - No big central hole possible
  - Recesses at front faces for electronics and strain gages

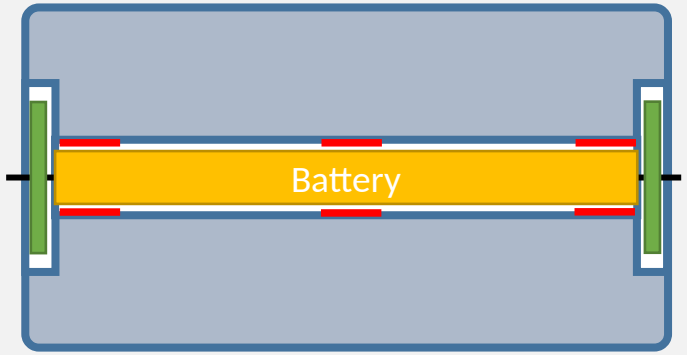



- Bigger Rollers (≥ 40 mm in diameter)
  - Rechargeable / non-rechargeable
  - Energy Harvesting possible

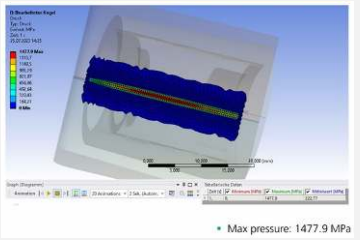



+ uniform contact pressure




+ more battery runtime






Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Rolling element integrated measurement technology / i4M Smart Roller

- Rolling element with integrated sensor technology for load (strain gauges) and rotational movement (MEMS IMU)
- **Rolling element diameter approx. 23 mm**
- **Shaft speeds up to 1500 rpm**
- Highly compact, battery-powered radio telemetry (proprietary i4M protocol)
- Integrated load measurement technology
  - Applied to the front faces, no central hole
  - 24-bit resolution, low noise, **2 kHz sampling rate**
- Integrated motion measurement technology
  - MEMS-based inertial measurement unit (IMU)
  - Triaxial acceleration sensor (accelerometer)
  - Triaxial rotation rate sensor (gyrometer)
  - 16-bit resolution, low noise, **1.6 kHz sampling rate**
- Power supply via integrated rechargeable battery, > 3 h continuous live measurement time
- Rechargeable on the test bench via contact pins

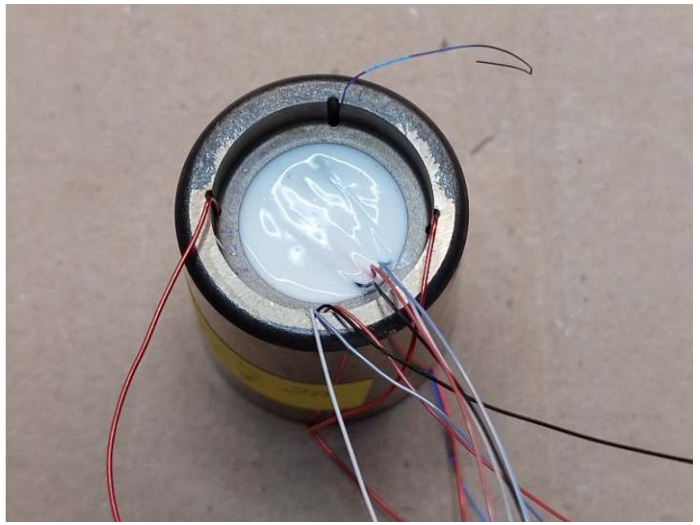


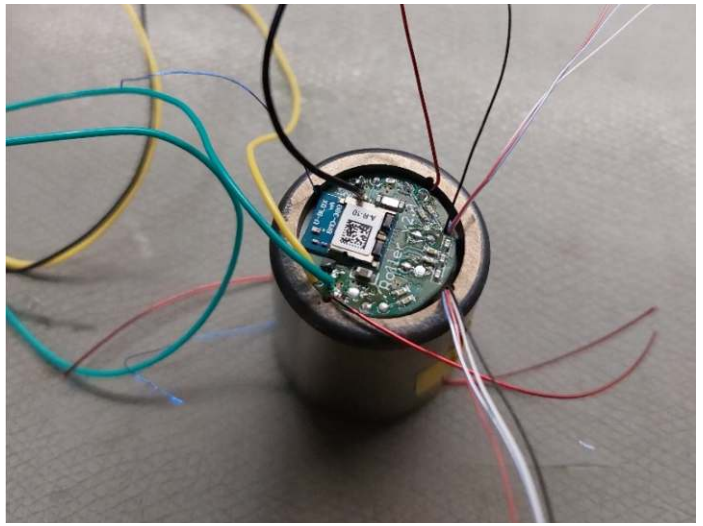


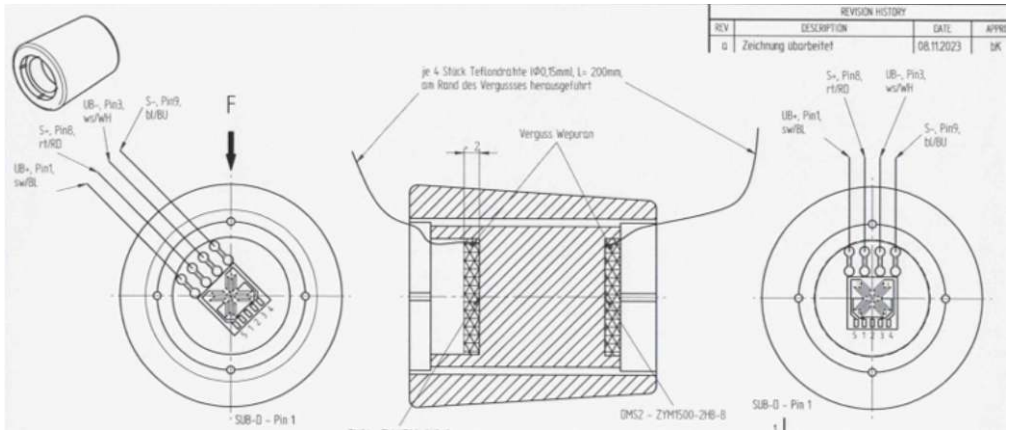
Fraunhofer IWES
i4M technologies GmbH intelligence for mechanical systems

# Rolling element integrated measurement technology / i4M Smart Roller

- Strain gages applied to front sides
- No through hole necessary
- Two electronics circuit boards
  - Measuring circuit board with sensors and radio telemetry
  - Power circuit board with battery and charging electronics
- Hardened rolling element manufactured using spark erosion process
- Completely encapsulated with epoxy resin







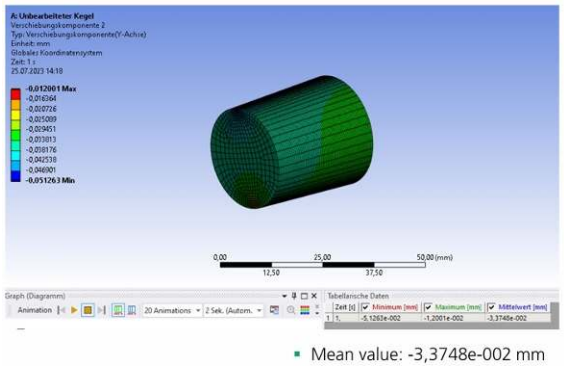


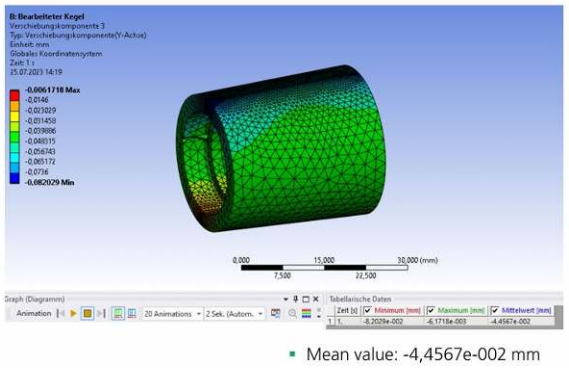

Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

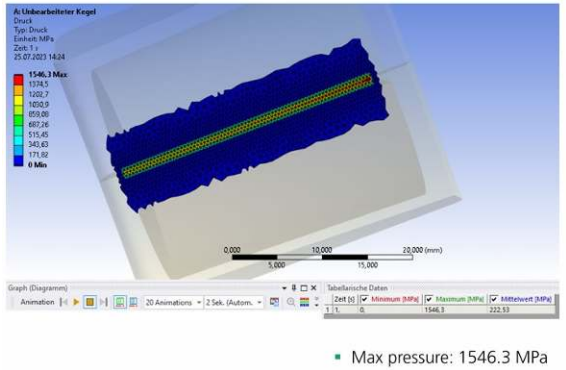
# Rolling element integrated measurement technology / i4M Smart Roller

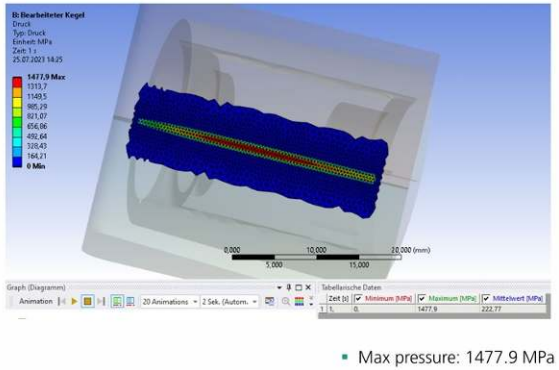
- The necessary machining of the rolling elements to integrate the measurement technology changes the system behavior
- Finite element simulations provide information about how stiffness and pressures change
- The test parameters must take these changes into account (e.g. adjustment of loads)




Change in the stiffness of the rolling element




Change in contact pressures

Source: FE simulations provided by Fraunhofer IWES



Fraunhofer IWES

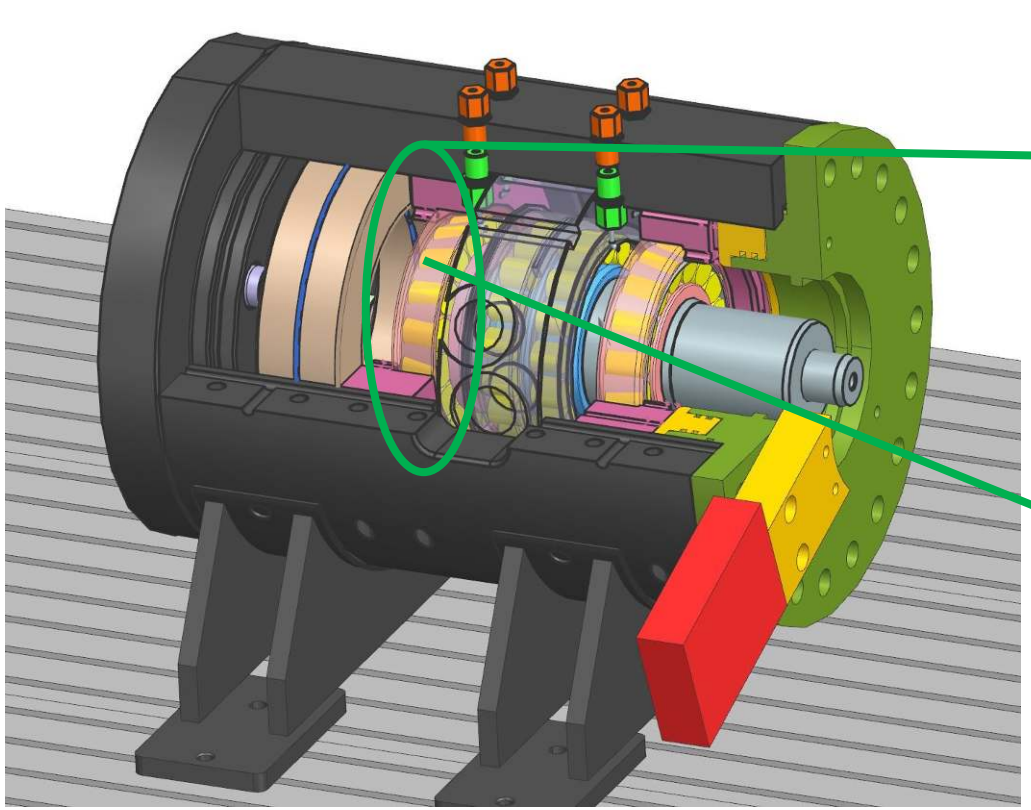
i4M technologies GmbH intelligence for mechanical systems

# Outline

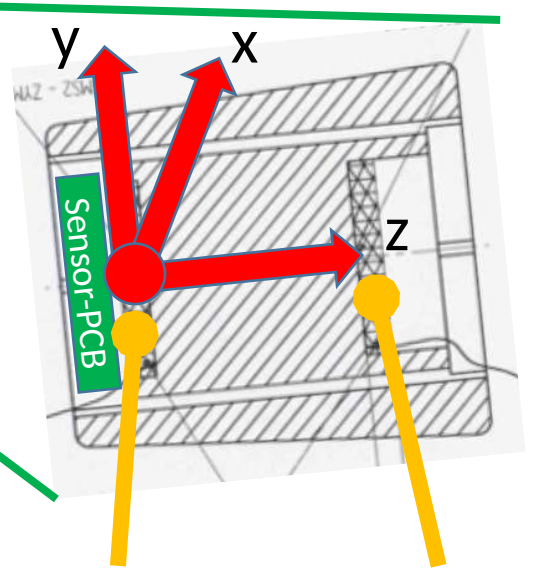

1 Introduction, overview, and motivation
2 Test bench setup and bearings
3 Rolling element-integrated measurement technology
4 Data and analysis methods
5 Results
6 Summary and outlook

# Data & Analysis Methods

- Definition of the coordinate system of the rolling element-integrated motion sensor technology
- X and Y lie in the plane of the rolling element end faces, Z lies on the rolling element axis of rotation
- Strain gauge channel 1 is located under the measuring PCB (smaller end face),
  strain gauge channel 2 is located under the power PCB (larger end face)










Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Data & Analysis Methods

- Discussion of the delivered data using an example (250 shaft-rpm)
- Load variation on test bench: Increase in radial force 0 to 90 kN / axial force 0 to 30 kN



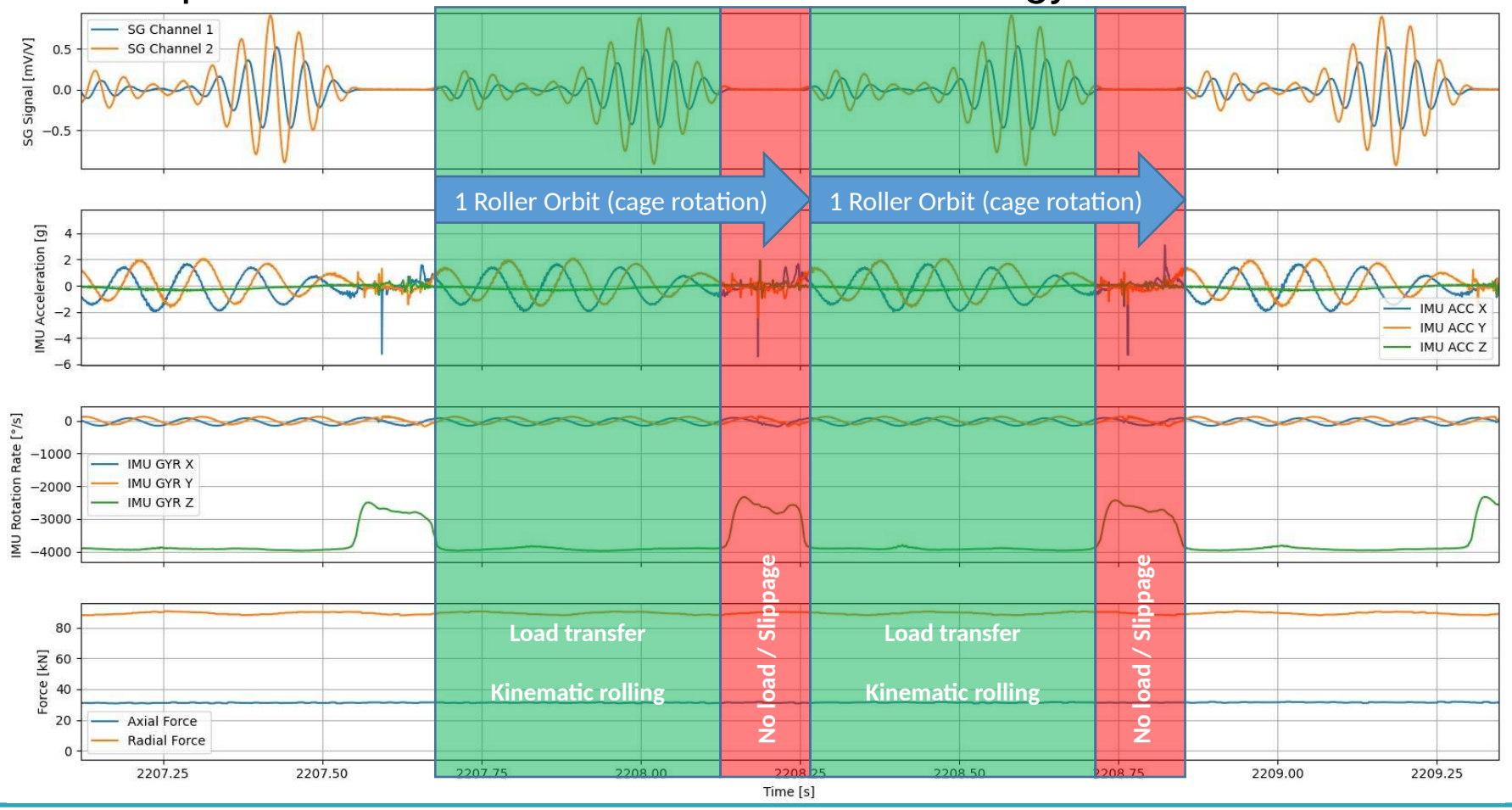



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Data & Analysis Methods

- Discussion of the delivered data using an example (250 shaft-rpm, 90 kN rad. / 30 kN ax. Detail)
- Identification of slip conditions based on accelerometer and gyrometer data





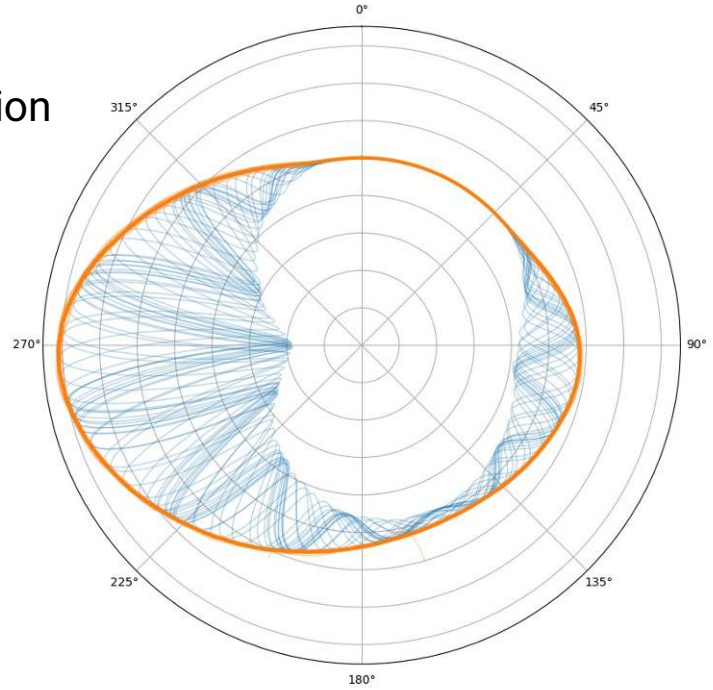

Fraunhofer IWES

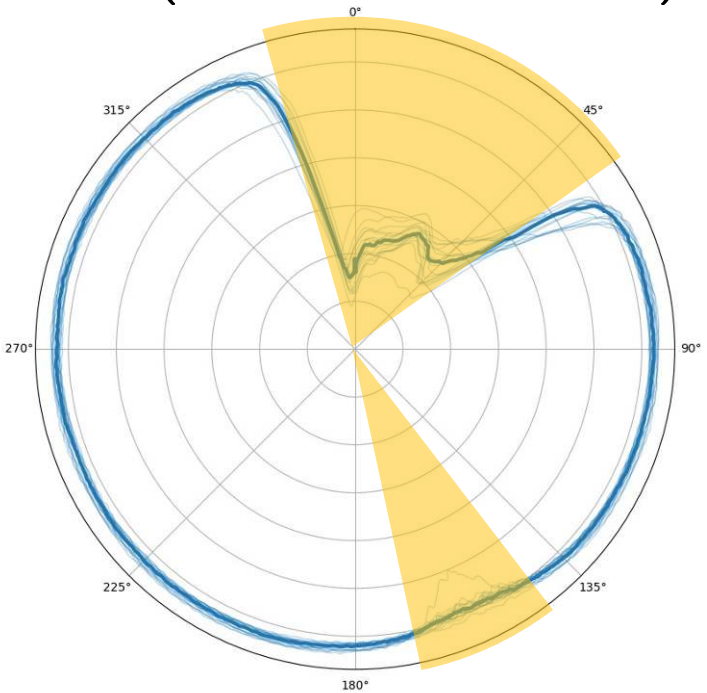
i4M technologies GmbH intelligence for mechanical systems

# Data & Analysis Methods

- Rotational speed of the rolling element from Z-Gyrometer (optionally zero crossings of the rolling element X/Y accelerations), rotational speed of the shaft (for kinematic reference) from test bench data
- Rolling element orbit position (= cage rotation angle and not shaft rotation angle!) from the progression of the rolling element Z acceleration
- Plots of all measured variables over the orbit possible (90 kN rad / 30 kN ax):

Roller Load Distribution (SG Channel 2)



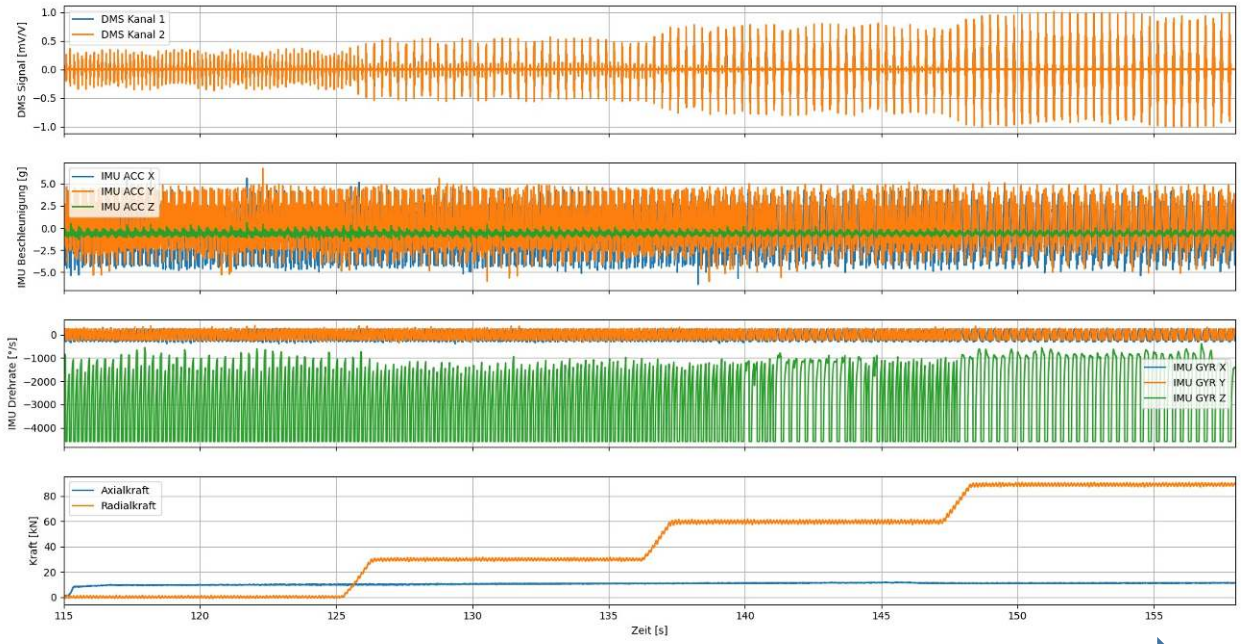

Roller Slippage



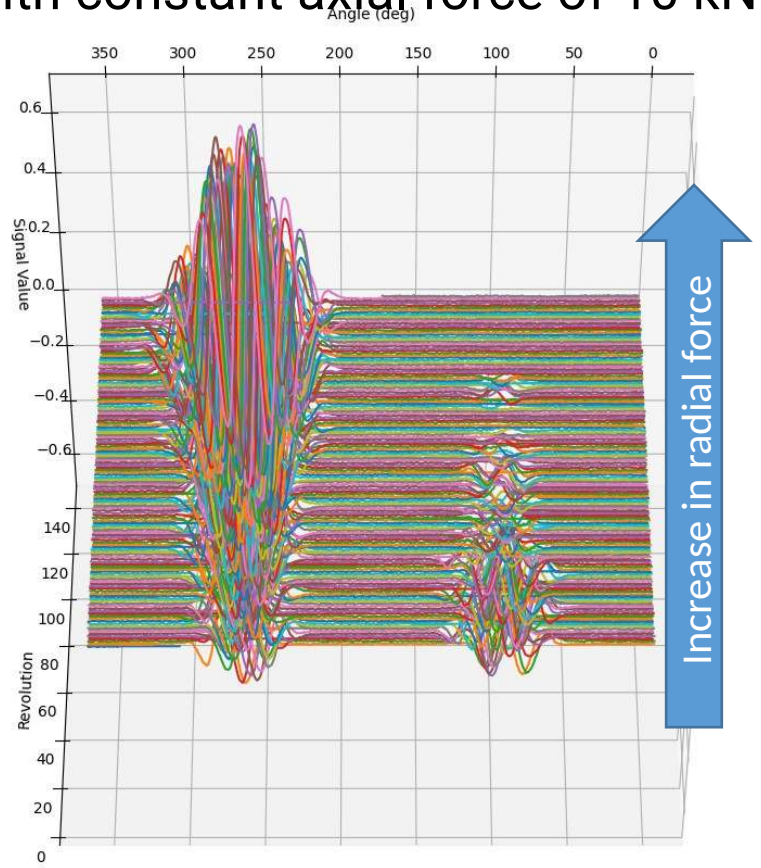
Fraunhofer IWES
i4M technologies GmbH intelligence for mechanical systems

# Data & Analysis Methods

- Measurement data can be broken down into individual revolutions and temporal developments can be displayed from revolution to revolution
- Boundary condition: Increasing radial force 0 to 90 kN with constant axial force of 10 kN




Increase in radial force




Increase in radial force



Fraunhofer IWES

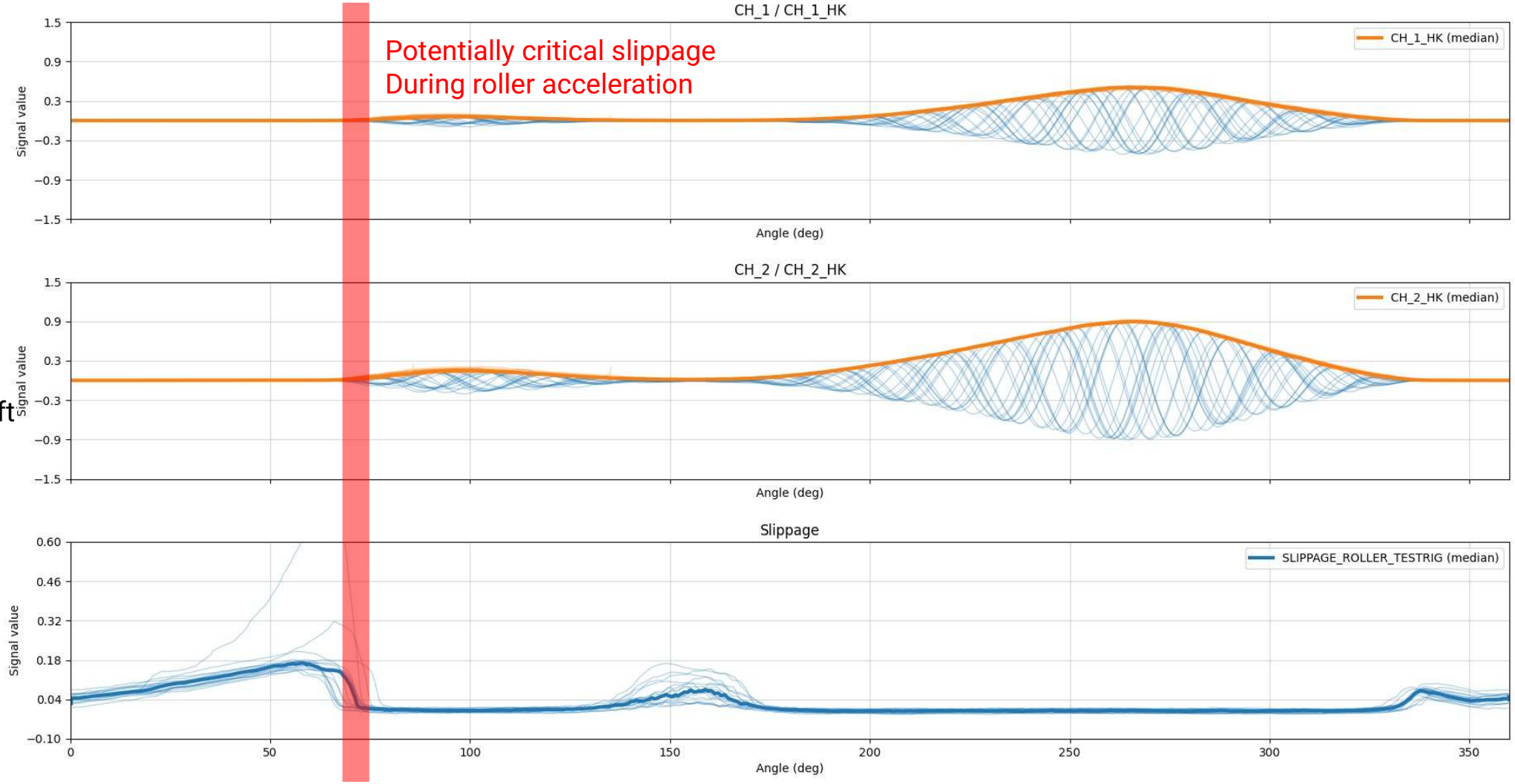
i4M technologies GmbH intelligence for mechanical systems

# Outline


1 Introduction, overview, and motivation
2 Test bench setup and bearings
3 Rolling element-integrated measurement technology
4 Data and analysis methods
5 Results
6 Summary and outlook

# Results and evaluation – Influence of axial load under quasi-static conditions

Radial: 90 kN
Axial: 0 kN
250 rpm Shaft



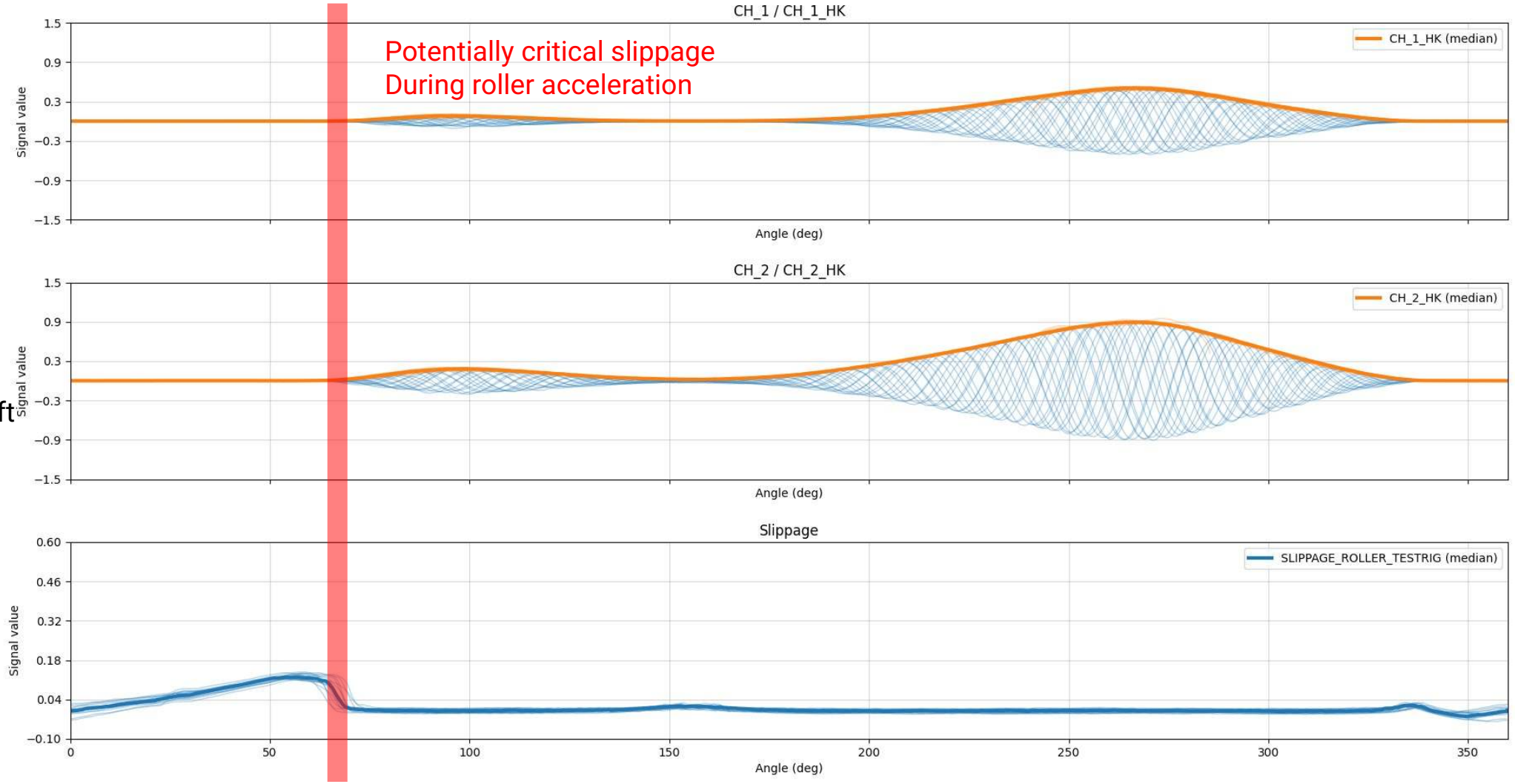



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Influence of axial load under quasi-static conditions

Radial: 90 kN
Axial: 10 kN
250 rpm Shaft



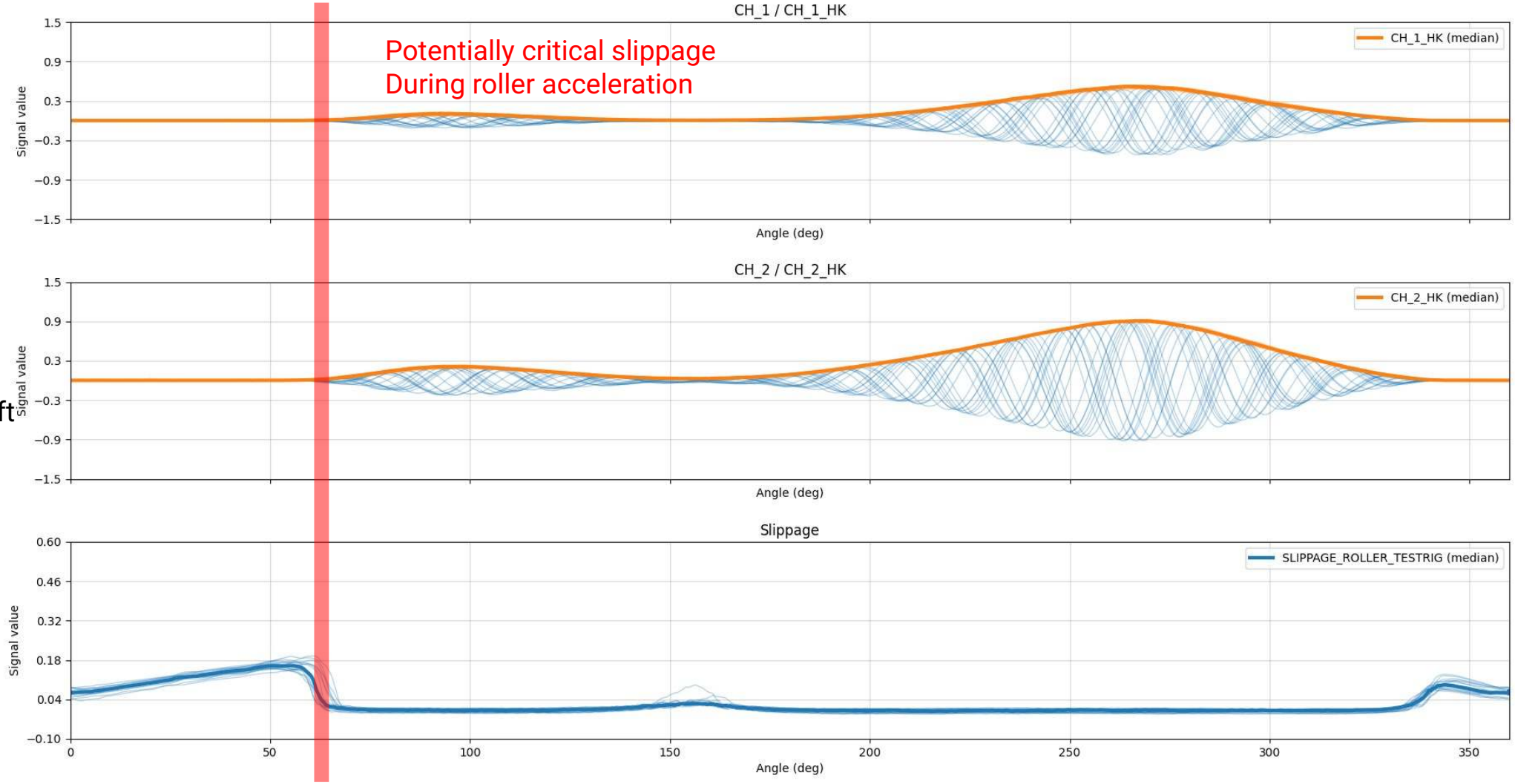



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Influence of axial load under quasi-static conditions

Radial: 90 kN
Axial: 20 kN
250 rpm Shaft



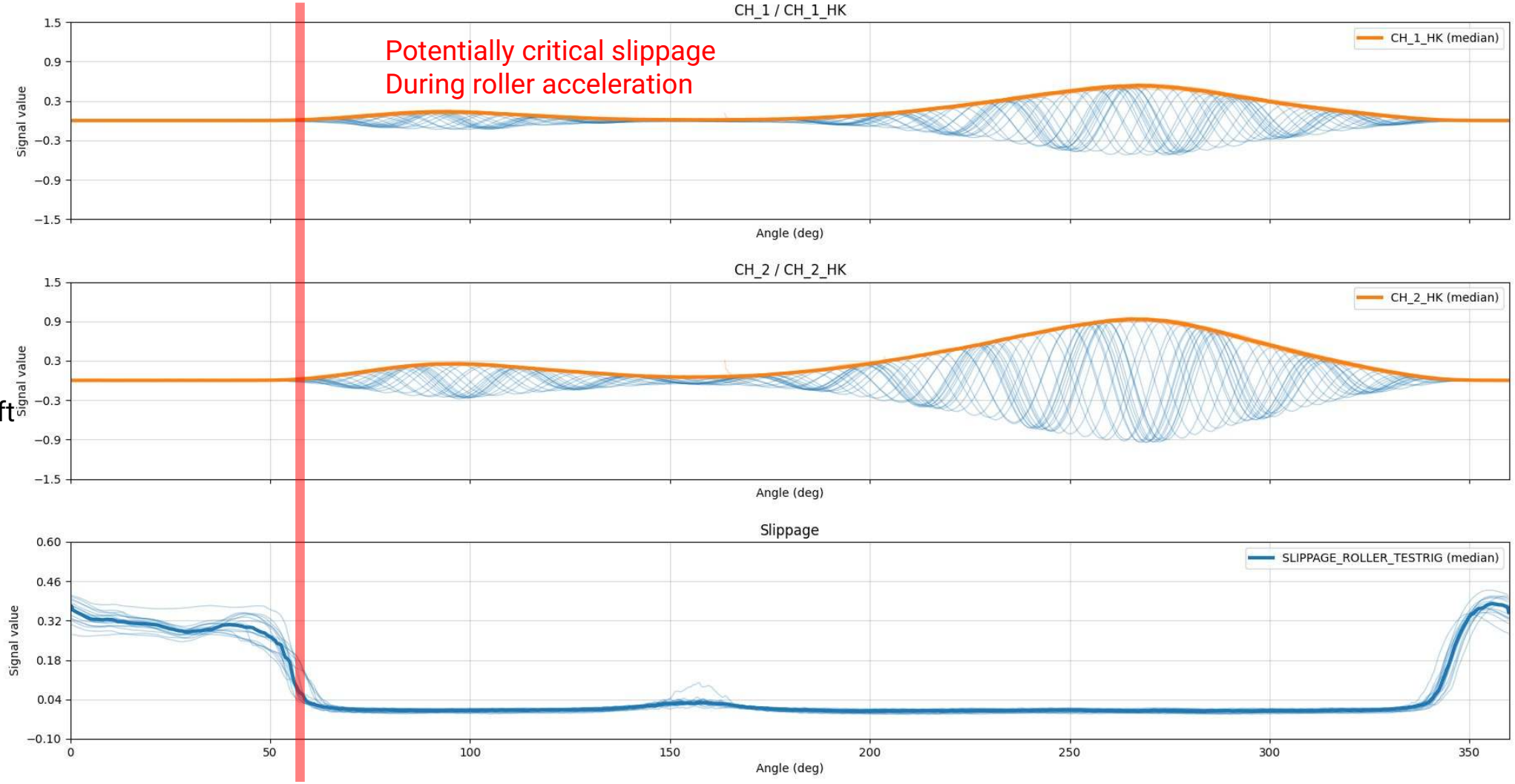



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Influence of axial load under quasi-static conditions

Radial: 90 kN
Axial: 30 kN
250 rpm Shaft



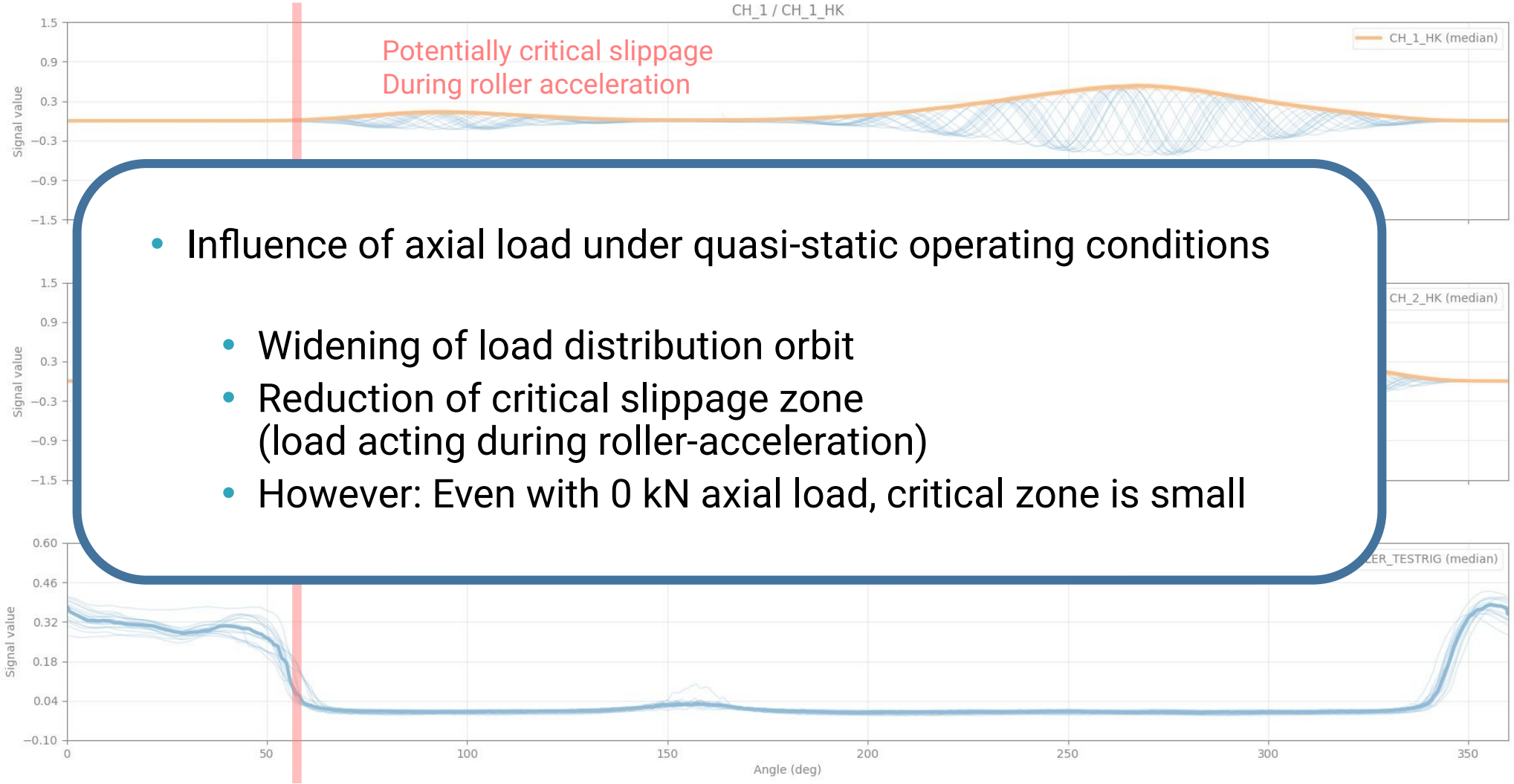



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Influence of axial load under quasi-static conditions

Radial: 90 kN
Axial: 30 kN




- Influence of axial load under quasi-static operating conditions
  - Widening of load distribution orbit
  - Reduction of critical slippage zone (load acting during roller-acceleration)
  - However: Even with 0 kN axial load, critical zone is small



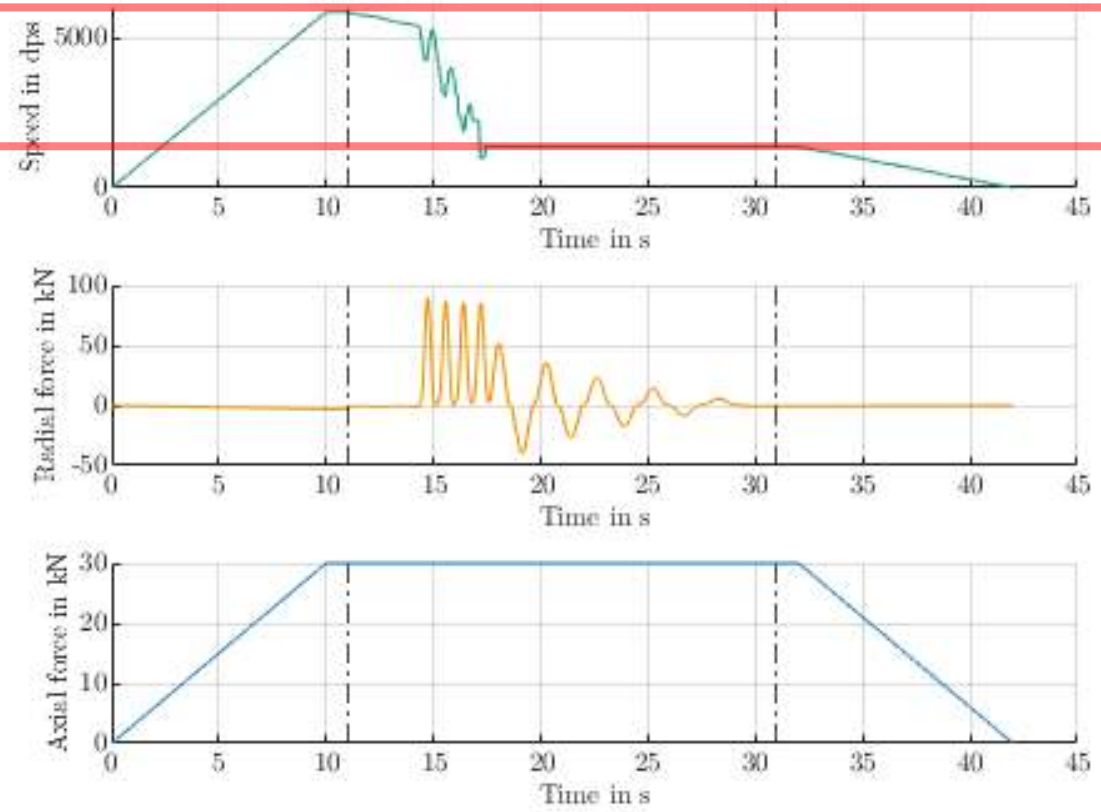
Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event

Start Shaft Rotation-Rate: 5800 °/s = 967 rpm
Start Roller Rotation-Rate: **15200 °/s** = 2532 rpm




End Shaft Rotation-Rate: 1305 °/s = 218 rpm
End Roller Rotation-Rate: **3420 °/s** = 570 rpm

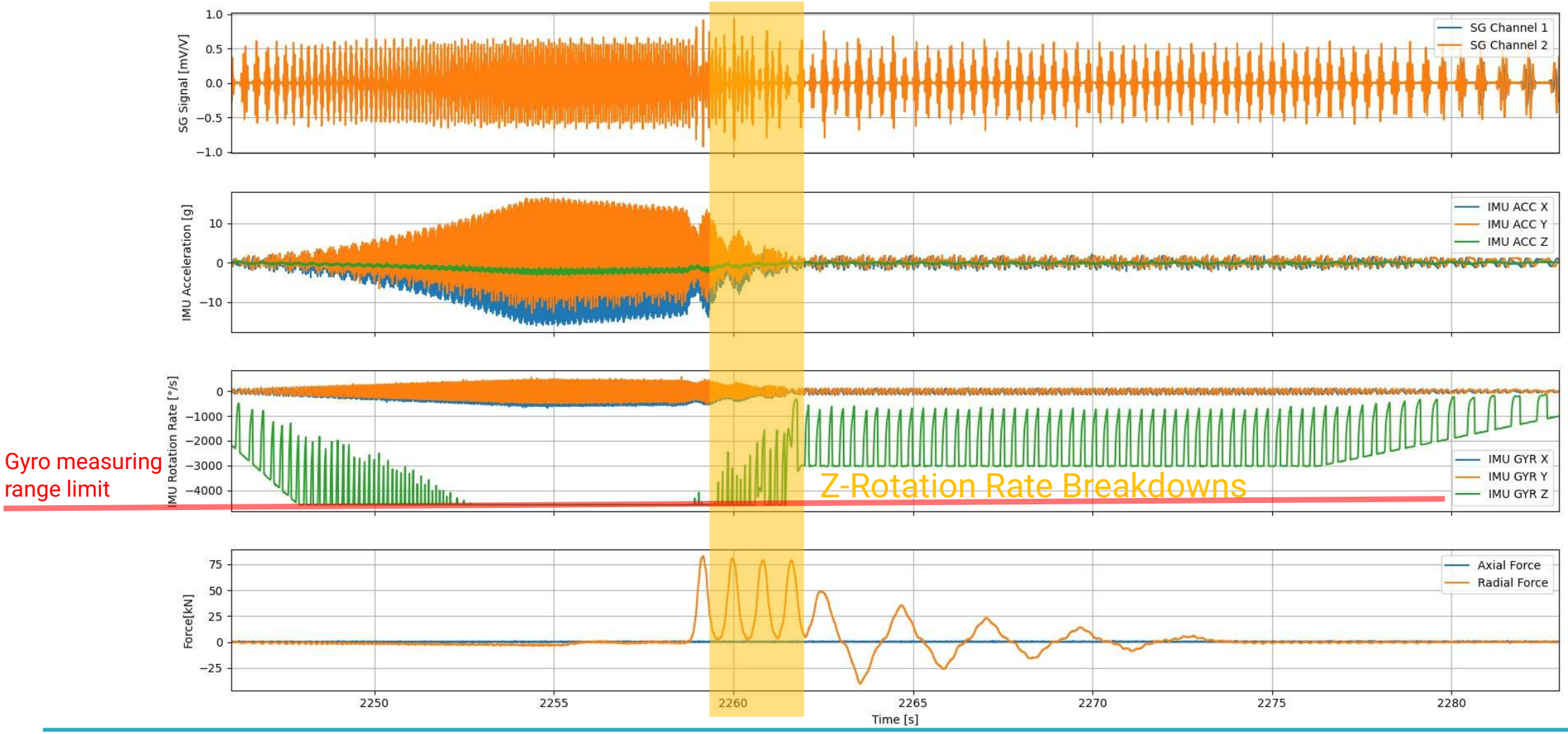
**Z-Gyro Range of the used roller is max. ca. ± 4500 °/s**
**Current Smart Rollers can measure higher rotation rates**
X/Y Accelerations can be used as an alternative to calculate Roller RPM up to higher speeds but with reduced time-resolution



Fraunhofer IWES
i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, no axial load



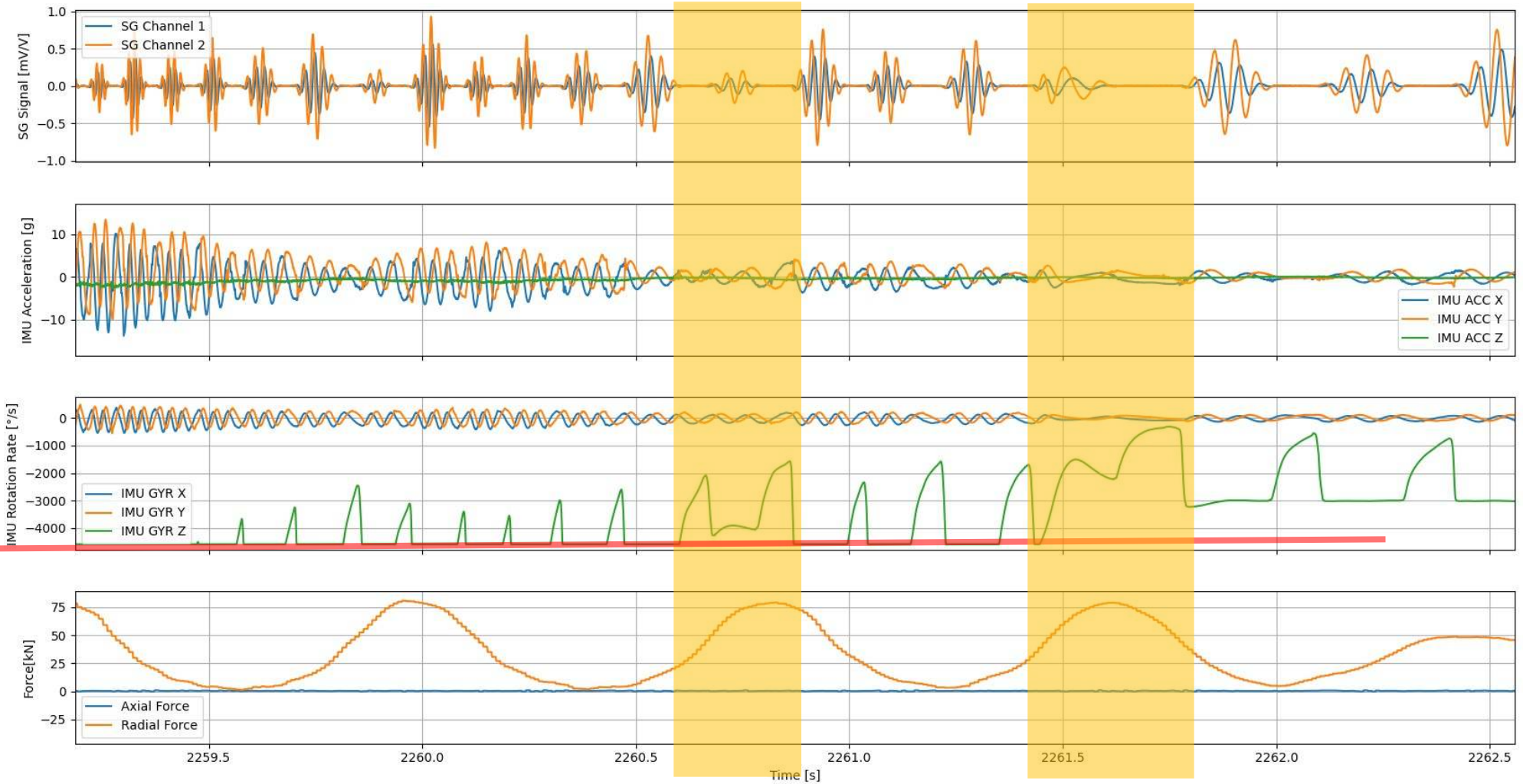



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, Detail, no axial load




Gyro measuring range limit

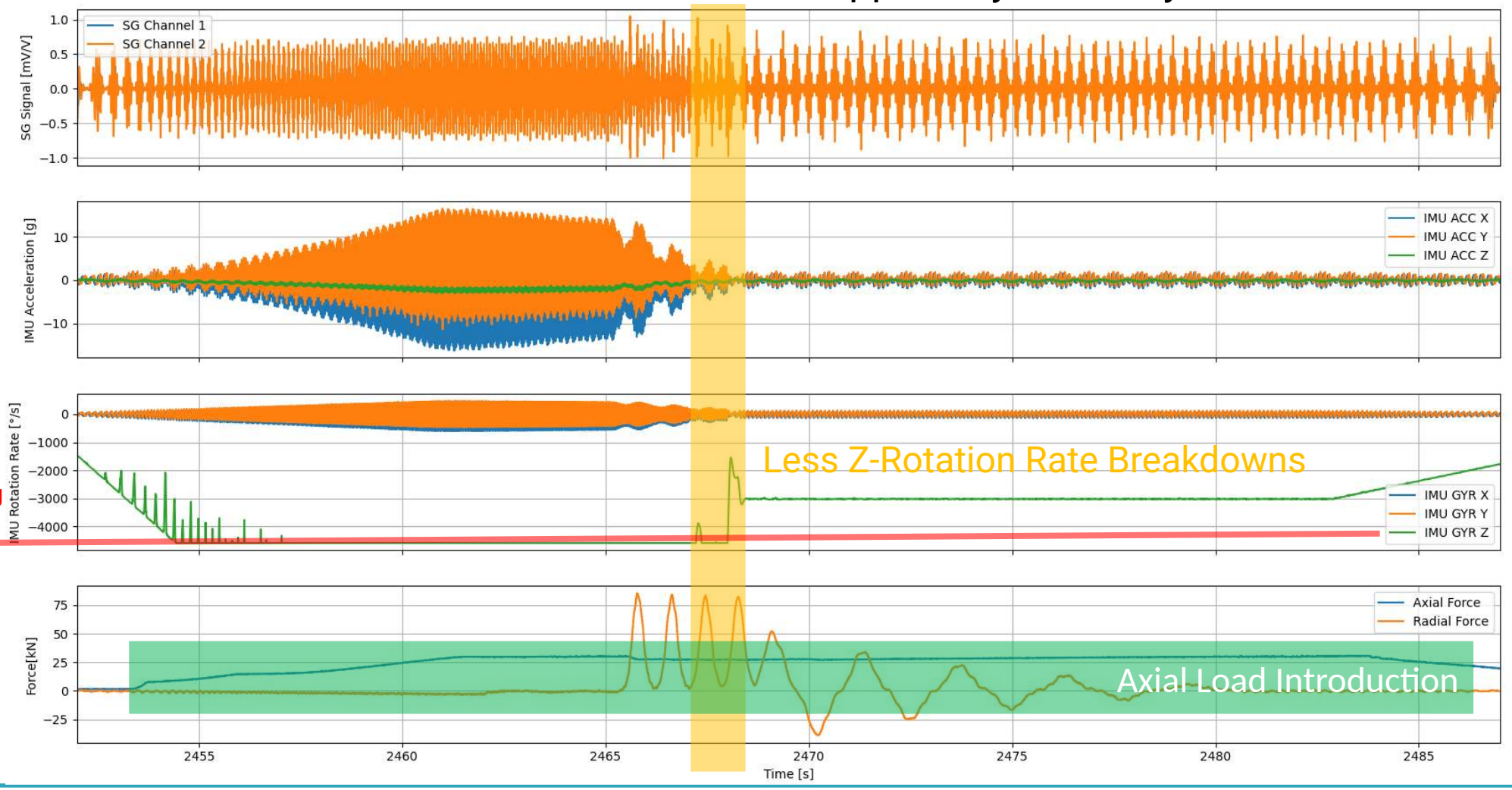


Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, 30 kN axial load applied dynamically




Gyro measuring range limit

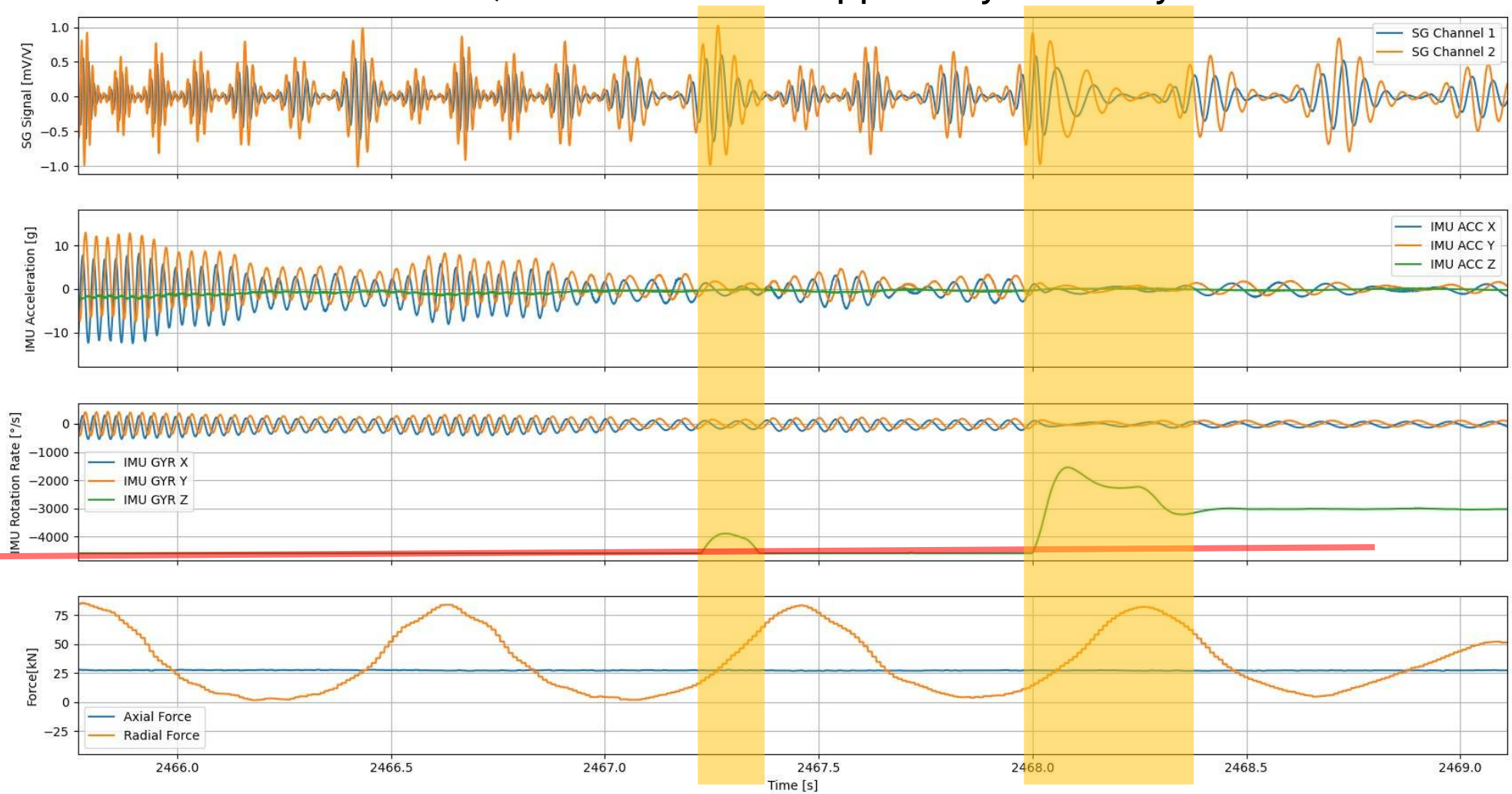


Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, 30 kN axial load applied dynamically




Gyro measuring range limit

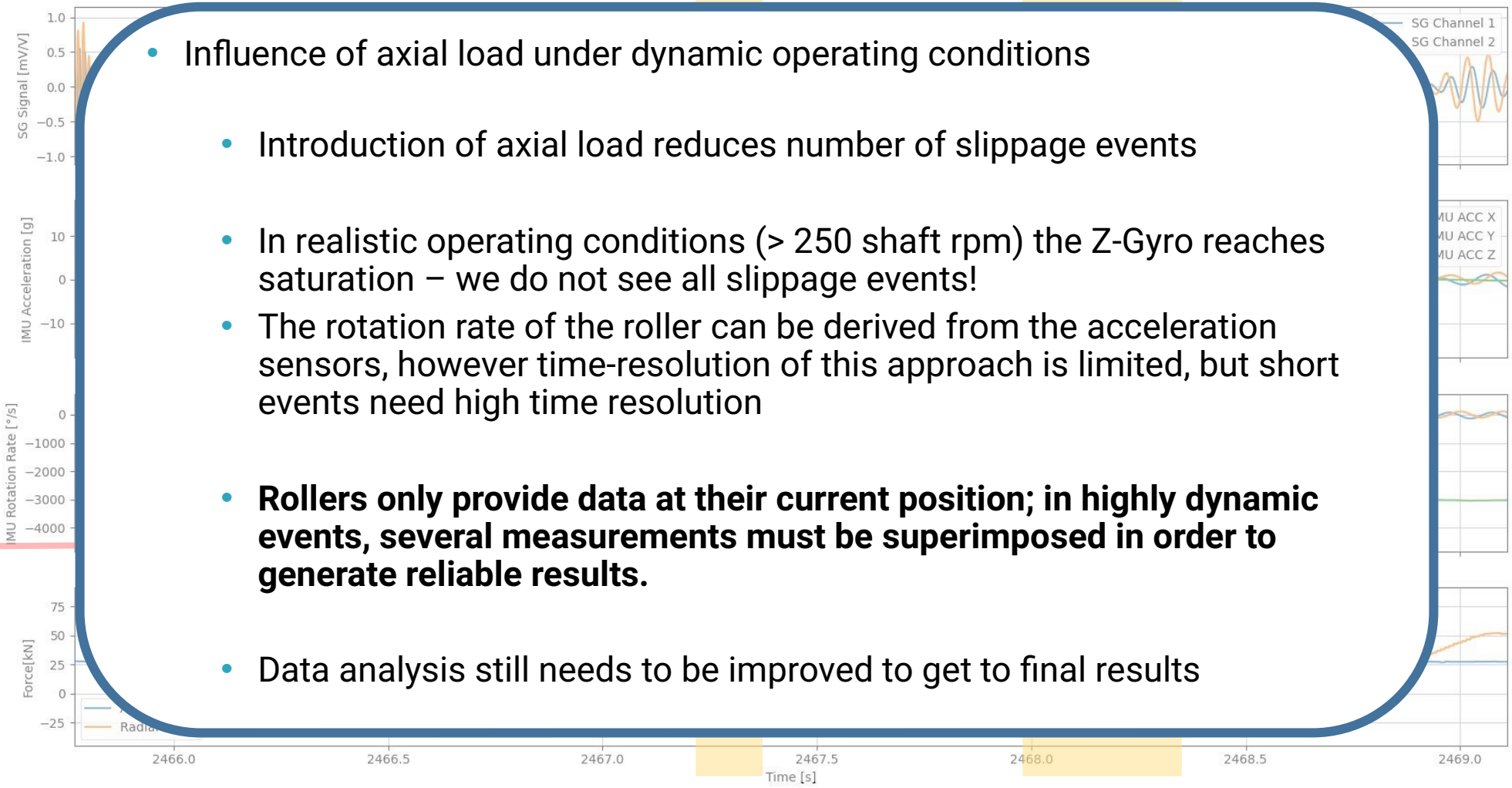


Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, 30 kN axial load




- Influence of axial load under dynamic operating conditions
  - Introduction of axial load reduces number of slippage events
  - In realistic operating conditions (> 250 shaft rpm) the Z-Gyro reaches saturation – we do not see all slippage events!
  - The rotation rate of the roller can be derived from the acceleration sensors, however time-resolution of this approach is limited, but short events need high time resolution
  - **Rollers only provide data at their current position; in highly dynamic events, several measurements must be superimposed in order to generate reliable results.**
  - Data analysis still needs to be improved to get to final results

Gyro measuring range limit



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Outline

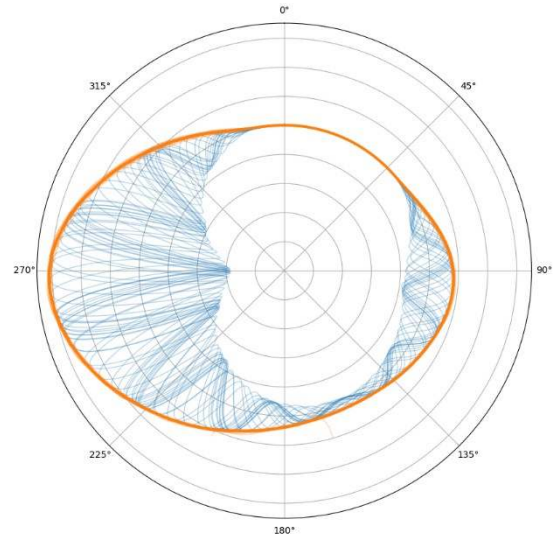

1 Introduction, overview, and motivation
2 Test bench setup and bearings
3 Rolling element-integrated measurement technology
4 Data and analysis methods
5 Results
6 Summary and outlook

# Summary & Outlook

- Integration of i4M's “Smart Roller” technology possible in smaller, faster-rotating bearings
- Compact, robust, reliable solution with high data rates and low energy consumption
- High-quality kinematic and load data from the rolling element
- Weakening of small rolling elements must be taken into account



- As expected, the introduction of axial bearing force reduces slippage
- However, under dynamic conditions, further analyses must be carried out.




- **Lesson learned: critical slippage zones are small – you need high time resolution / high sampling rates and high Gyro ranges to make them visible!**



Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems

# Contact

## Thank you very much for your attention!




**Martin Noll**
Managing Director

Tel.: +49 (0)241 56 00 22 00
martin.noll@i4m-tech.de

**i4M technologies GmbH**
Försterstr. 5
52072 Aachen
Germany

Tel.: +49 (0)241 56 00 22 00

www.i4m-tech.de





**Matthias Stammler**
Senior Engineer

Tel.: +49 (0)471 14290-522
matthias.stammler@
iwes.fraunhofer.de

**Fraunhofer IWES**
Am Schleusengraben 22
21029 Hamburg
Germany

Tel.: +49 (0) 471 14290-522

www.iwes.fraunhofer.de





**Valentin Meimann**
Managing Director

Tel.: +49 (0)160 78 43 668
valentin.meimann
@mml-solutions.com

**MML Service Solutions GmbH**
Am Rabenhufen 20
46487 Wesel
Germany

Tel.: +49 (0)160 78 43 668

www.mml-solutions.com




Fraunhofer IWES

i4M technologies GmbH intelligence for mechanical systems